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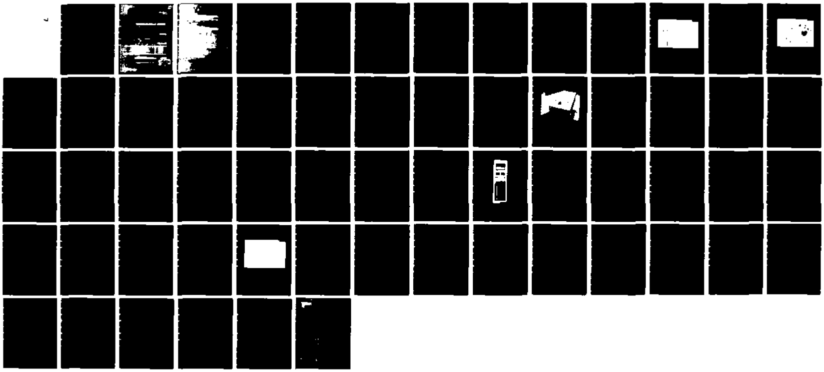

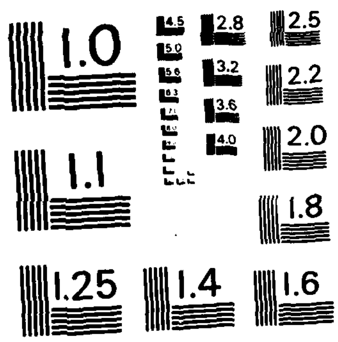

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

PANORAMIC SKY MONITOR (PANSKY)

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Group 94

PROJECT REPORT ETS-68

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LEXINGTON MASSACHUSETTS

Abstract

A system has been designed and built for optically detecting clouds at night. Based on a low light level television camera with a fisheye lens, the system can detect clouds either by moonlight or by stellar occultation. The system is integrated with a scheduling program for the Experimental Test System (ETS) of the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) system to allow operations on partly cloudy nights.

Contents

I. INTRODUCTION

A primary task of the Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) is the maintenance of the deep space object catalog. Two types of activity are defined in the GEODSS specification for this purpose. The first is manuever query, which is a quick look at a satellite to see if it is near its predicted position (has not manuevered). The second activity is the taking of positional data on a satellite to refine its orbital element set. These observations of known satellites must be scheduled to maintain the catalog in an orderly manner and to use the optical sensor efficiently.

The contractor for the operational GEODSS system has chosen to use a fixed schedule, generated during the day, which allots a time interval to each satellite. If the actual observation runs longer than the time interval, either the current observation must be truncated or the next time slot encroached upon. If the observation is finished quickly, the system idles until the next time slot. The Experimental Test System (ETS), on the other hand, uses a dynamic scheduler, which runs on demand throughout the night. An indefinite length of time is allocated to each satellite. When the observation is finished, the scheduler is run to determine the next object. The current dynamic scheduler considers visibility, priority, and the distance the telescope must travel to the next object. Priority includes tasking from the Space Defense Center (SDC) and the length of time since the last observation. But since we can't see through clouds with our optical sensors, local cloud cover should also be considered. The goal is to be able to work through holes in the clouds on partly cloudy nights. By using the sensors more efficiently, more useful data can be taken on such nights.

As an indication of the number of nights that clouds are a problem, Fig. 1 shows the cloud condition statistics for the last 5 years at the ETS. The category of clear nights means that no clouds are present. The category of overcast means the sky is completely covered and the site effectively shut down. The category of partly cloudy, which covers about 35% of the available nights, means there are clouds present, but also significant holes between them. It is for nights in this category that dynamic scheduling with a cloud monitor is useful. It is anticipated that at a tropical site the partly cloudy category will include a larger percentage of nights than at the ETS, which is at a relatively high and dry location.

Detecting clouds optically can be done in at least two ways. If the sun or moon is up, the clouds are illuminated and are easily seen. However, if there is no moon, clouds can be lighter or darker than clear sky, and so can not be detected easily by surface brightness. One reliable way to detect clouds is to look for stars, which are obscured by clouds.

The cloud monitor resolution should be at least 10°, based on cloud velocities and the time required to look at a satellite. To have a star grid of this resolution requires roughly 400 stars. The dimmest stars are about 5th magnitude, and since we wish to determine their brightness accurately, a system sensitivity of 6-7th visual magnitude is required.

A cloud detection system has been implemented at the ETS. The ETS system was designed to work in both the bright and dark sky modes. However, due to problems of linearity of the camera system, the star detection mode has not been fully tested. The bright sky mode has as its basic display the processed picture of the sky. The dark sky mode adds to the picture graphic symbol

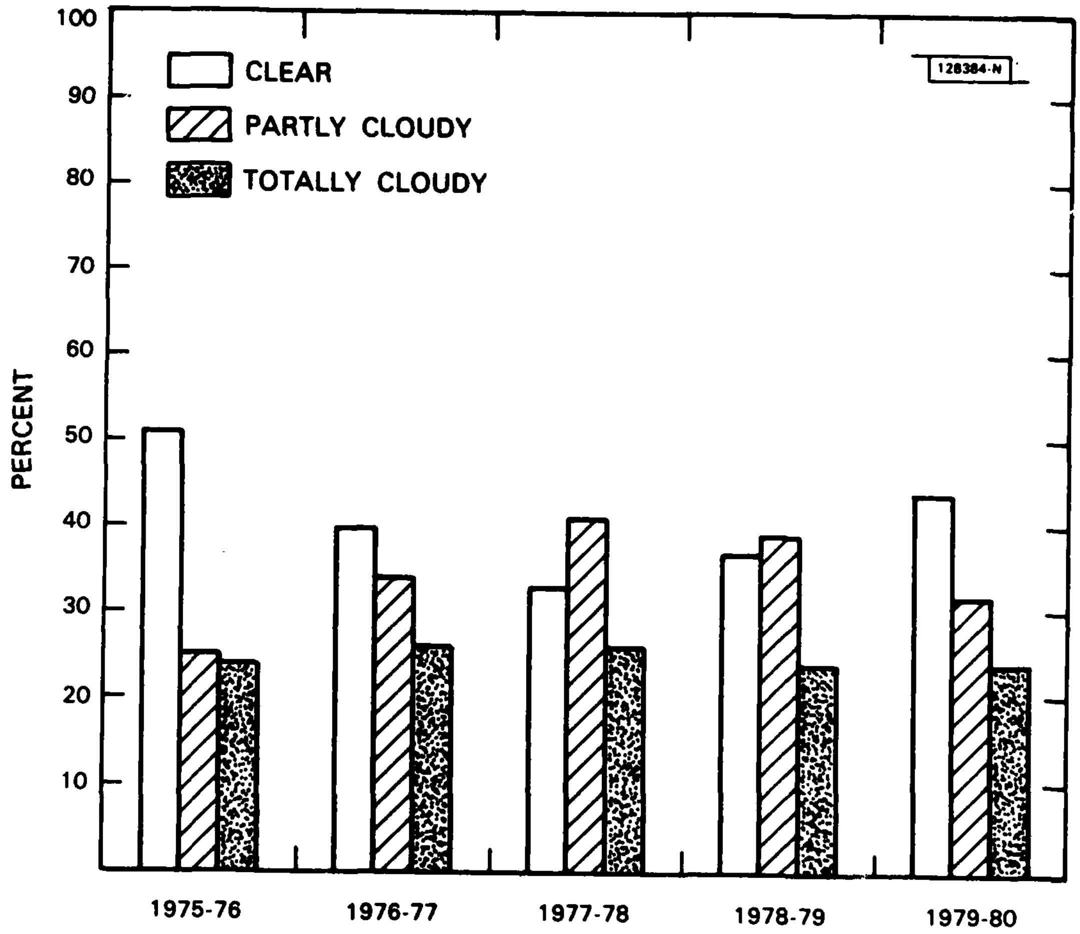

Fig. 1. Cloud cover statistics at ETS.

overlays representing the atmospheric extinction value at the star position. The ETS system is known as the Panoramic Sky Monitor, or PANSKY.

It is necessary to have both sky modes available for two reasons. The dark sky mode, which looks for stars, can be easily fooled by fine structures in illuminated clouds into believing a star can be seen when it is actually a cloud being viewed on a bright night. The second reason is that with television type sensors, the lens must be stopped down on bright nights to avoid saturation of the sensor by the moon and bright clouds. This reduces system sensitivity such that fewer stars can be seen. Therefore both sky modes are needed because neither one will work well over all sky conditions.

Four levels of sky monitor integration into the overall satellite detection system are possible. Both bright and dark sky modes can be used at all levels of integration.

In the simplest level, a camera is placed on the roof and the picture made available to the operator. No video processing is required for the bright sky mode. This saves the operator from having to walk outside to observe the cloud cover. An example of the view obtained on a clear night is given in Fig. 2.

In the second level of integration, a connection to the central site computers is made, and the sky monitor obtains the current telescope positions. It then generates an overlay showing where the telescopes are pointed. In this mode the operator knows exactly where he is in relation to clouds, but the operator is still responsible for taking action based on the information. If a dynamic scheduler is available, the operator can defer observation of satellites which are observed to be in a cloudy direction, and the scheduler

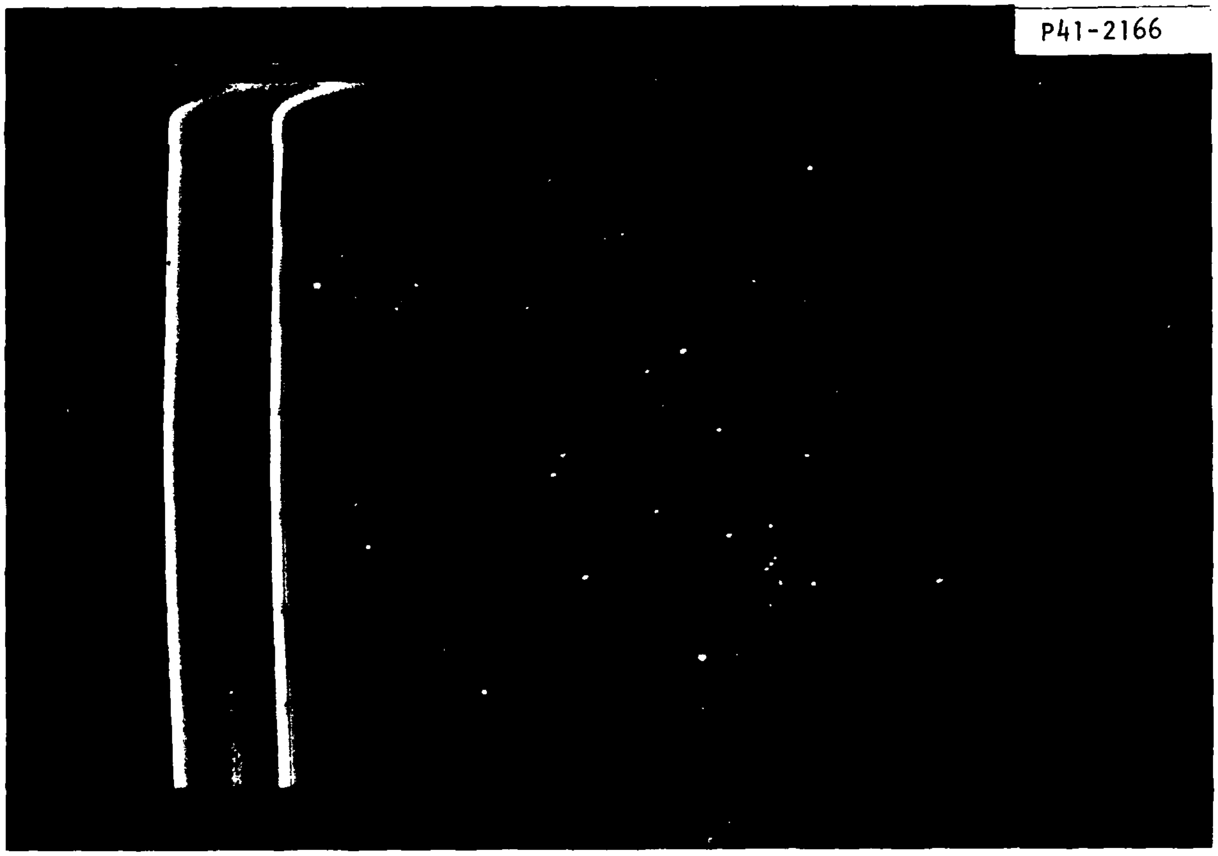

Fig. 2. Clear sky image from PANSKY.

will suggest another satellite for observation which may or may not be located in a clear area. The sky monitor system must implement metric calibration for this mode of operation.

In the third level of integration, the semi-automatic mode, the sky monitor receives the positions of candidate satellites from the dynamic scheduler running in the main site computers. The satellites are ranked by the scheduler, and their positions overlayed on the sky image. The operator then has the option of rejecting the 'best' satellite and choosing one which is in a clearer area of sky. The operator is still making the judgment of sky quality. An example of this type of display on a moonlit night is shown in Fig. 3.

In the fourth level of integration, the fully automatic mode, the sky monitor itself assesses sky quality, and makes a recommendation either to the operator or directly to the dynamic scheduler. While the fully automatic mode provides the most convenient and potentially the fastest system operation, it is also most likely to malfunction under difficult cloud and lighting conditions. It is probably not worthwhile to make the cloud discrimination algorithm sophisticated enough to work under the total range of conditions likely to be encountered.

The ETS system was integrated to the semi-automatic level, and was tested in the bright sky mode for 3 months by Air Force personnel during routine operations. The system was well received, with the major complaint being the additional time taken by the dynamic scheduler program, which was a function of the central site computers, not the sky monitor.

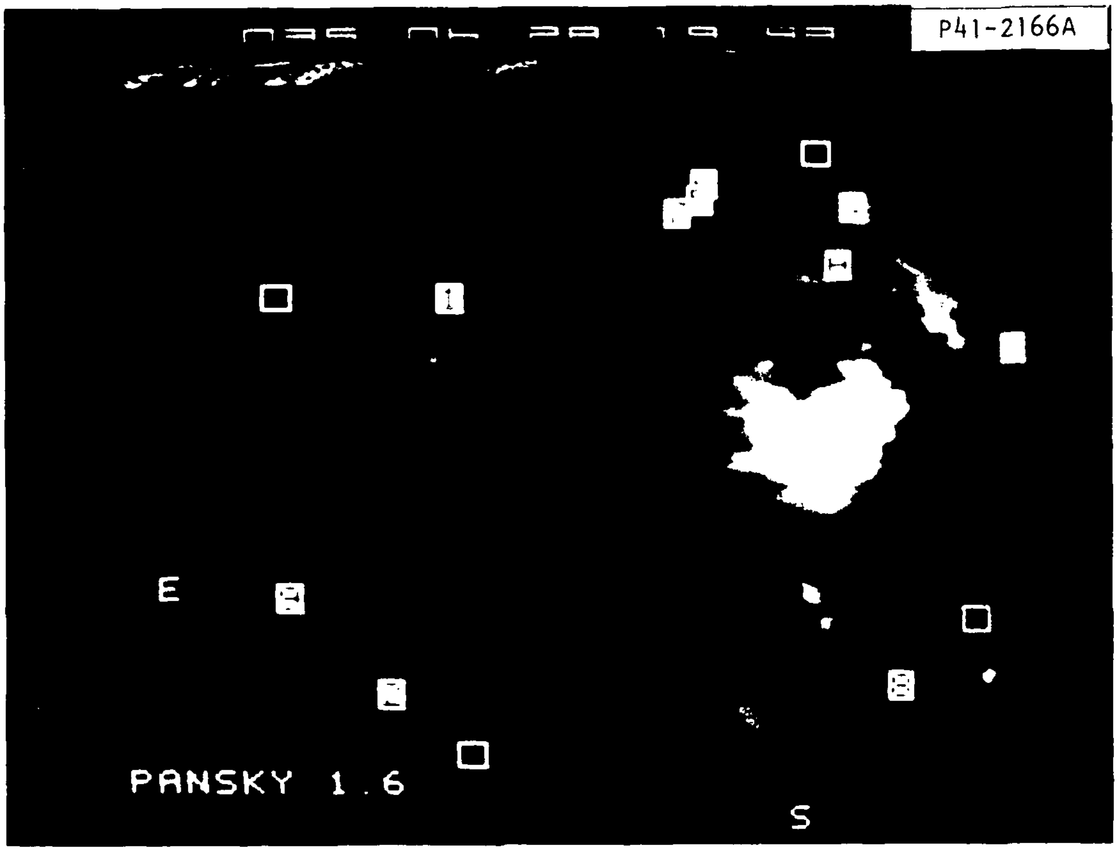

Fig. 3. Moonlit image from PANSKY with schedule choices shown. "A" denotes current telescope position. The calibration light sources are surrounded by boxes.

In the semi-automatic mode it was found necessary for the scheduler to provide up to 30 different satellite choices. The top choice tended to be in the vicinity of the current telescope position. This is not surprising because the scheduler is designed to minimize telescope motion. It was the second 10 satellites which started to provide some real choice in which area of the sky to operate.

II. SYSTEM OVERVIEW

The Panoramic Sky Monitor as installed at the ETS will now be described, with detailed descriptions of the hardware and software in later chapters. Figure 4 is a simplified hardware block diagram.

The system is based on a 40 mm faceplate ebsicon (electron bombarded silicon) low light level television camera. The television camera is mounted on the rooftop pointing at the zenith. A Nikon 16 mm f2.8 fisheye lens gives a view of the entire sky down to 15° elevation in all directions. The television signal goes to a digital video processor which provides signal integration, background subtraction, and computer access to the image. It also provides graphic and alphanumeric overlay capability on the system television outputs.

A microcomputer controls the entire system and provides the interface to the main site computers. The microcomputer does all star detection and controls the camera active calibration system. An internal catalog of 370 stars is present. The catalog formation procedure is described in Appendix B. A control panel of 32 buttons is used to operate the system. Once the sky monitor is calibrated and running little operator interaction is needed.

A lunar occulter has been provided. This is a small motor driven paddle which is used to block the moon to help avoid sensor saturation.

It was found necessary to provide an active system to maintain metric calibration of the ebsicon camera. The whole image of the sky shifts relative to camera sync as the system warms up, and the image size varies with the camera trim and focus settings. Furthermore, the camera is not exactly aligned with north, and image rotations as a function of camera settings cannot be excluded. The image of the sky obviously needs to be calibrated if we are

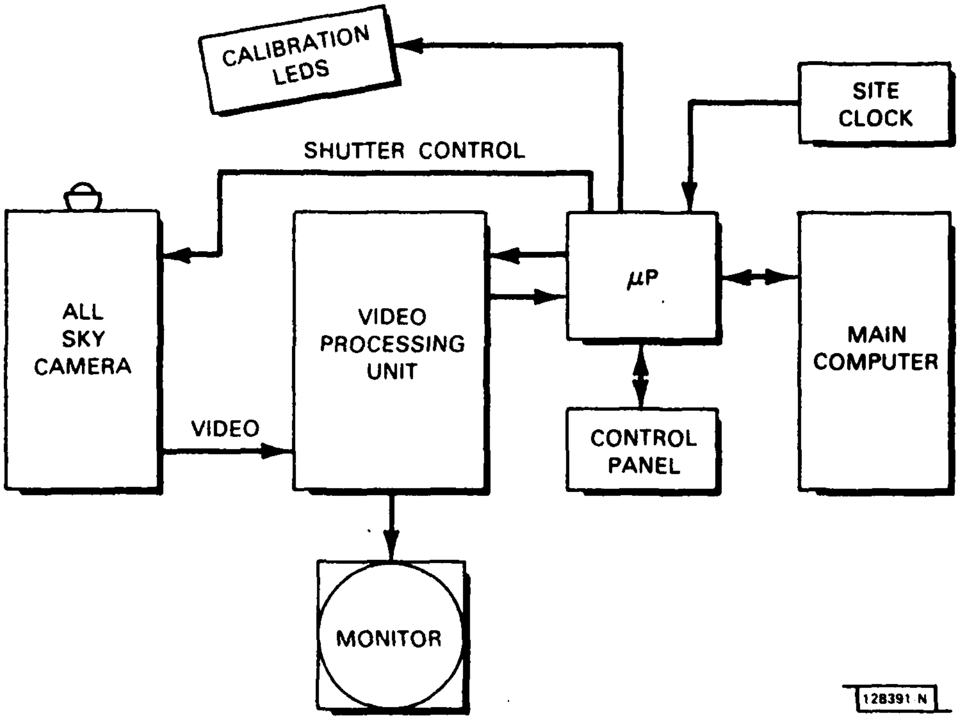

Fig. 4. Simplified block diagram of PANSKY system.

going to show where a telescope is pointing or look for a star which may be obscured. Since the image parameters change, the system cannot be calibrated once and be assumed to hold its calibration.

Because the calibration needs to be constantly maintained, a calibration system was devised which allows rapid coarse calibration and which then actively tracks slow changes in image metric parameters. A set of four artificial stars was installed such that they appear at the four corners of the field of view. These calibration sources are used as landmarks to maintain the metric calibration and correct for image translation, rotation, and scale changes. The calibration parameters can be adjusted from the control panel, and part of the procedure of bringing up the system is to manually adjust the calibration model to the point where the automatic system can lock on to landmarks. The automatic system will then maintain the calibration during normal operations.

The calibration system was aligned by determining the azimuth and elevation of the landmark light sources. This is done by entering a special program which requires a diagnostic terminal. The system is first calibrated by manually adjusting the parameters, using the stars as the position reference. This must, of course, be done on a clear night. The position coordinates of each landmark are then adjusted to agree with the current calibration parameters. The positions are held in non-volatile memory, and are eventually made part of the program PROM. The entire alignment procedure takes about 15 minutes and only has to be done when the camera head is physically disturbed.

One of the calibration light sources is used as a light intensity standard, so that the system can be photometrically calibrated. This reduces system sensitivity dependence on lens aperture setting, dust on the lens, or camera tube and preamplifier gain.

Basic system operation starts by integrating 256 fields of television signal into a 15 bit summation memory. If background subtraction is enabled, the camera is then electronically shuttered, and 256 fields are subtracted from the summation memory. If the dark sky mode is being run, the positions of all the stars are calculated. The shutter is opened, and the active calibration routine is run on the stored image. The image is then transferred to an 8 bit image memory to provide a stable display. If the dark sky mode is being run, the system then looks at the stored image for all the stars currently above horizon limits. At each star position the star signal is measured and compared to a catalog value. A graphic symbol is then overlayed on the video representing the extinction at that location. If the bright sky mode is being run then stars are not used, and the output picture is the stored image with a few titles and calibration marks as overlays.

While the above process is repeating, telescope and satellite positions are updated on overlays roughly every second. All dynamic scheduler interaction is through the main site computer and its terminal on the main console.

III. SYSTEM HARDWARE

The Panoramic Sky Monitor (PANSKY) hardware consists of several systems, and a detailed hardware block diagram is given in Fig. 5.

All Sky Camera

The television camera system is based on a 40 mm diameter faceplate ebsicon built by RCA. The particular tube used was a developmental model, but similar tubes are available from several manufacturers. The ebsicon type of tube contains a photoemissive surface and a target made from a silicon wafer consisting of a large array of diodes. Photoelectrons are accelerated by a high potential and electrostatically focused on the target. When the high energy electrons strike the target, they produce large numbers of electron-hole pairs, on the order of 2000 for each photoelectron. The charge is trapped in the junction of the diodes on the target and read off with a scanning electron beam. It is the photoelectron acceleration and collisionally induced electron-hole pair formation which gives the ebsicon its virtually noise free gain of 2000. It is this feature which gives the ebsicon its superior low light level performance. By the same token, this large gain is the cause of its poor high light level performance, because the sensor is easily saturated. When a bright point source is imaged on the faceplate, more charge is generated in the target than can be contained in the junction of a diode, and the charge will spread out on the target, giving a 'bloomed' image.

The camera system consists of three units, the camera head, the camera control unit, and the camera remote control unit. The camera head is located in the rooftop enclosure, and consists of the ebsicon, high voltage power

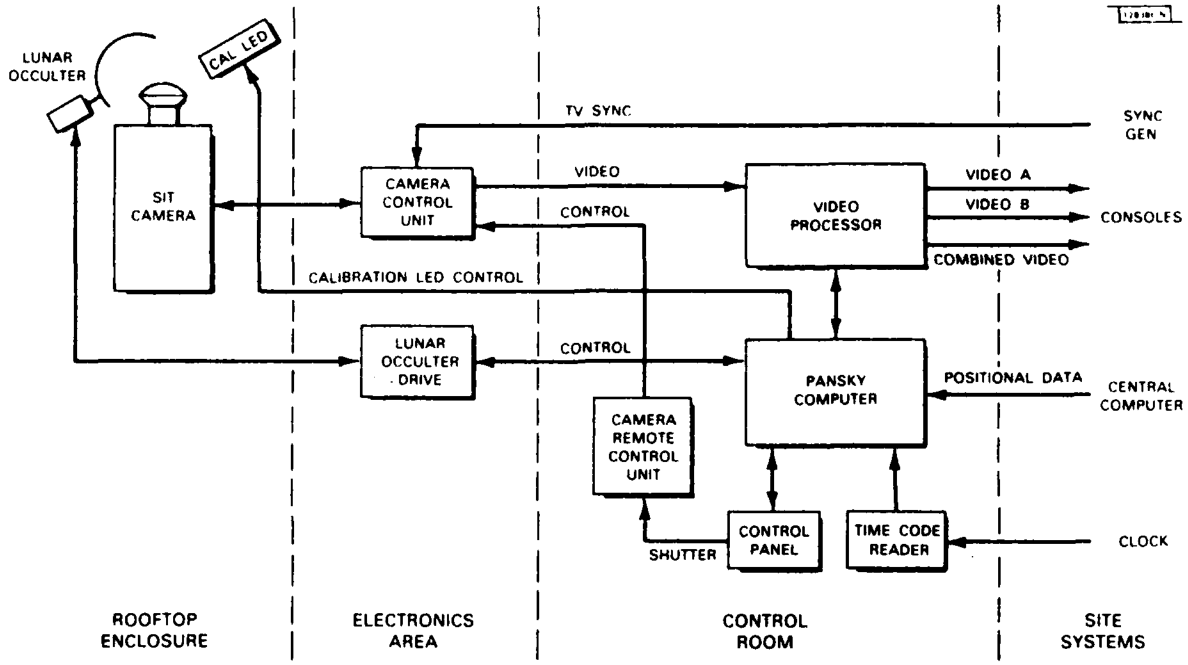

Fig. 5. Detailed block diagram of PANSKY system showing location of components.

supplies, and video preamplifier. Because it is in the rooftop enclosure, the camera head is subject to temperature and humidity extremes.

The rooftop enclosure is a steel box, painted white outside and black inside, with a deep hinged cover. The camera, calibration source, and lunar occulter all mount on a single aluminum plate. A rubber gasket seals the enclosure when the cover is closed. The enclosure must be closed during the daytime, because the extreme field of view of the fisheye lens will otherwise focus the sun on the camera faceplate, potentially damaging it even when the camera is not on. The ebsicon is susceptible to damage from high light levels, and should not be operated even during twilight conditions. A drawing and picture of the enclosure assembly are presented as Figs. 6 and 7.

Originally a glass dome was use to protect the lens from dust and moisture, but reflections of the moon and ground lights proved to be objectionable, and the dome was removed.

It was found necessary to provide positive ventilation of the enclosure at all times. Otherwise the enclosure walls would cool rapidly during the evening, drawing moisture through the electrical conduit from the building interior. During the day the sun would warm the walls, driving the moisture into the camera, now off and cool. On several occasions water dripped out of the camera head when it was removed for servicing. Often the problem was discovered by a degradation of the system due to water forming on the camera faceplate and lens rear element. We have had no further problems since installing an ambient air ventilation system.

The camera control unit is located in an electronics area adjacent to the rooftop enclosure, but within a climate controlled building. It contains

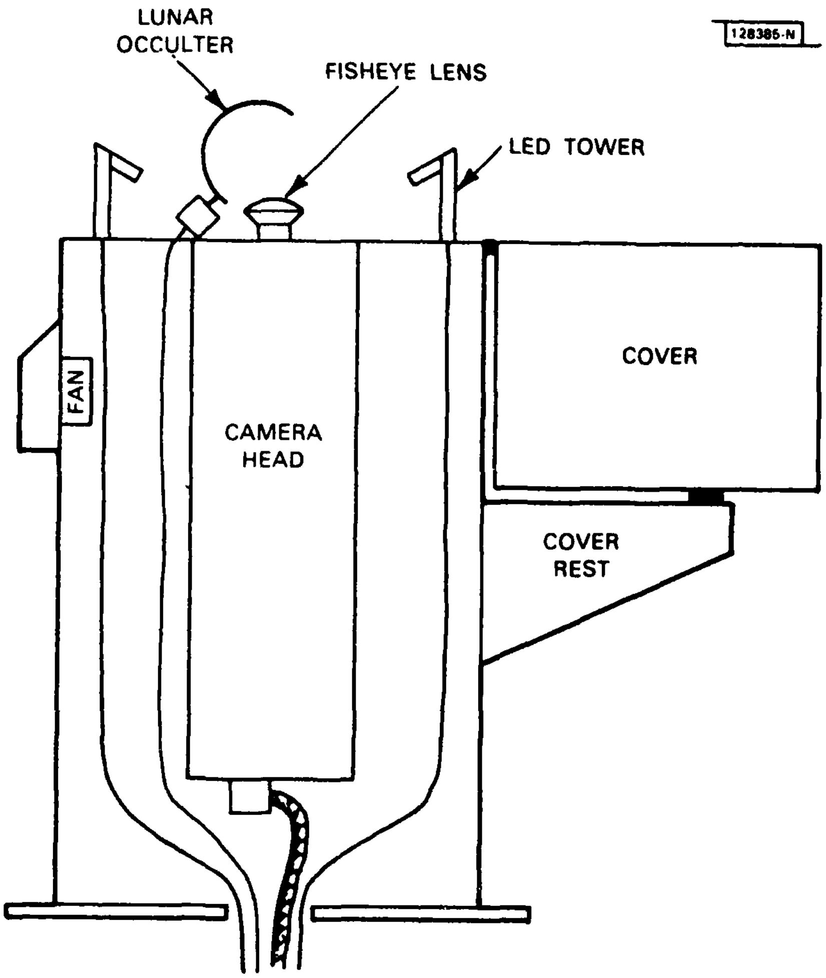

Fig. 6. Rooftop camera enclosure.

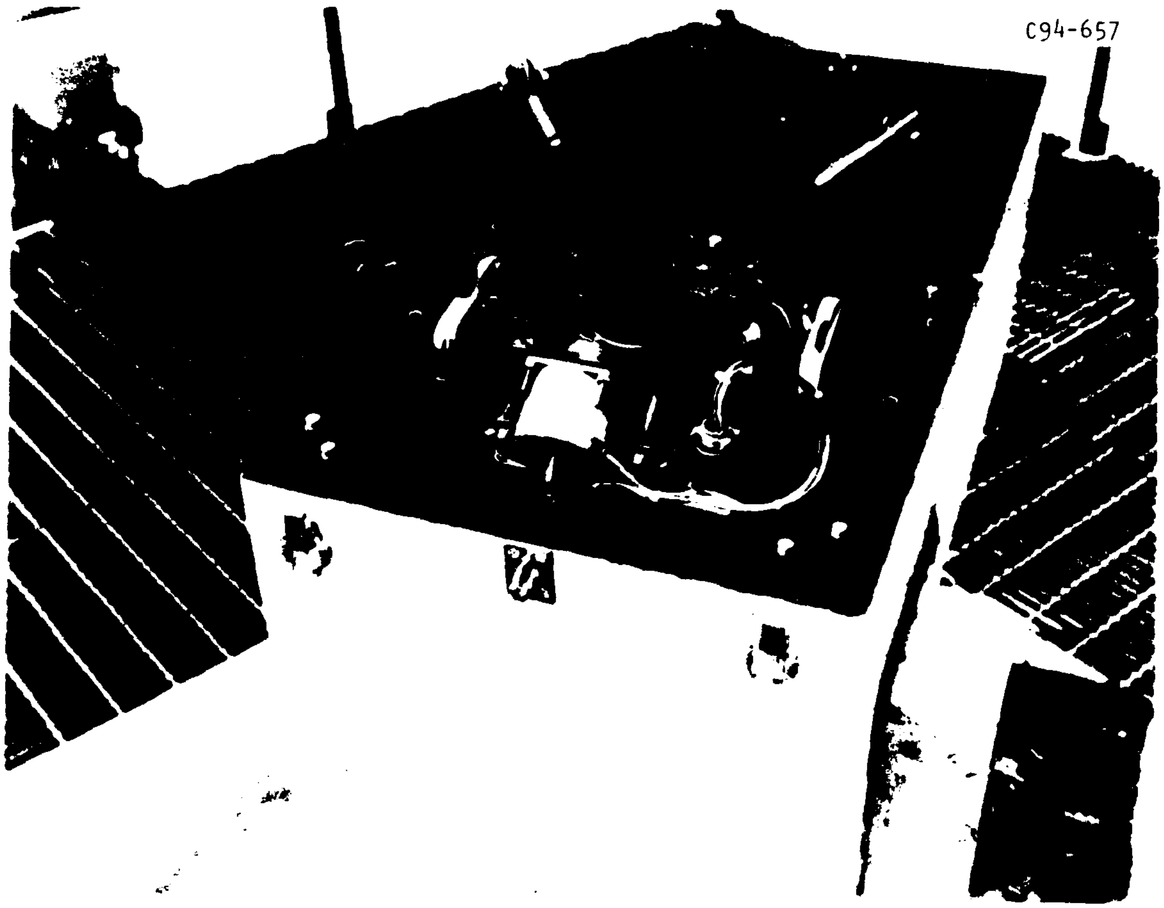

Fig. 7. Rooftop camera enclosure. The fisheye lens, LED calibration source towers and the lunar occulter are all visible on the top plate.

the horizontal and vertical sweep generators, grid and filament power supplies, and supplies low voltage DC power to the high voltage power supplies in the camera head. The camera control unit accepts separate sync, blanking, horizontal and vertical drive signals and produces two identical channels of composite video. The system is run as a NTSC standard 525 line, 30 hz frame rate interlaced system, and is therefore compatible with the ETS video distribution system and monitors. Under normal circumstances the camera control is never adjusted, as all common adjustments have been remoted.

The camera remote control unit resides in the main control room and is the normal operator and computer interface. It contains a master on/off switch for the camera system, a three position switch for high voltage control, and three trim controls for adjusting image size and focus. The high voltage control switch allows the tube high voltage to be either on, off, or computer controlled through a rear panel connector. The high voltage is turned off as a means of electronically shuttering the camera to allow instrument DC bias and target blemishes to be determined.

When the camera is turned on, it is first allowed to stabilize for roughly 5 minutes. It is then adjusted for focus and image size with the high voltage trim and focus controls, and then adjusted again for focus with the G3 control. The control adjustments are then iterated to provide best image focus and proper size. The edge of the target can be seen, as the beam oversweeps the target, so the target appears as a circle within the rectangular picture.

Once the camera is adjusted, the calibration system is manually adjusted to match the picture.

Calibration Light Sources

The calibration light sources are mounted in four towers located in the corners of the top plate of the rooftop enclosure. Each calibration light source is a miniature optical system consisting of a LED as light source, a .005 inch pinhole formed on high contrast photographic film, and a single element lens used to project the pinhole to infinity. When properly aligned, the calibration LED sources appear as fixed stars at the edge of the field of view of the television camera system.

The system is aligned by focusing the camera for stars on a clear night, then adjusting the towers until the source can be seen. Focus is adjusted for each calibration source by sliding the lens in and out. When the calibration source is in focus, a set screw is used to hold the lens in that position. The lens should not need to be refocused. Tower realignment may be required when lenses are changed or the towers are knocked out of alignment. The alignment procedure requires that a monitor be brought to the rooftop enclosure.

The LEDs are driven by computer controlled constant current sources. In the current system two sources were used, each driving two LEDs in series. The brightness is adjusted such that the calibration sources are as bright as a first magnitude star, and is done by direct comparison with known stars. The current sources are on the PANSKY Support Module in the PANSKY computer and connected to the rooftop enclosure by two coax cables.

Lunar Occulter

The lunar occulter is a computer controlled paddle used to block the direct light of the moon from reaching the PANSKY sensor. As previously

explained, the ebsicon tube will bloom when exposed to a bright point source. The actual size of the moon is such that it should fit in a single pixel, however, in practice it will bloom to as much as 10 pixels in diameter. In an attempt to reduce the overload on the tube the lunar occulter was constructed.

In the present implementation the paddle is manually positioned to block the image of moon. The manual positioning is accomplished by using buttons on the PANSKY control panel. The lunar occulter controller is based on a single chip microcomputer (MC68701) which communicates over serial lines with the PANSKY computer and generates the stepper motor driving sequence. Once positioned, the lunar occulter will move at sidereal rate of its own accord to maintain moon blockage. However, since the motor axis does not pass through the lens effective focal point, the paddle will not stay with the moon because no parallax correction is done. In practice the occulter may need to be manually repositioned every few hours, when the moon becomes objectionable again.

The lunar occulter contains limit switches to constrain its motion, and can be stowed at one extreme of travel. When the device is energized, it automatically seeks the limits of travel and internally calibrates its position, then moves to a stowed position.

The paddle and motor are mounted near the lens in the rooftop enclosure, and the controller is mounted in the electronics area near the rooftop enclosure, along with the camera control unit. The RS-232 communication lines use several lines of the cable connecting the camera control unit to the camera remote control unit.

Video Processor

The video processor receives analog television signals from the camera system. It digitizes these signals to 8 bits, and digitally integrates many frames to improve signal to noise ratio. It also optionally subtracts a background reading taken when the camera system is electronically shuttered. Subtracting a background removes many tube effects such as DC offset and target blemishes. The video processor makes the digitized image available to the PANSKY computer for star and calibration source recognition. The video processor further generates graphic overlays at the command of the PANSKY computer and produces three black and white television output signals. The system configuration and operation is totally software controlled.

The video processor is a Grinnel Systems GMR-27 unit with a resolution of 256 elements by 240 visible lines operating in a repeat field mode of standard NTSC television timing. There are two 8-bit deep image memories, one 7-bit image memory, and three single bit graphic memories. When acquiring and averaging data, the 7-bit memory can be combined with either of the 8-bit memories to form a 15-bit deep summation memory. Incoming video can be shifted down and then either added to or subtracted from the value currently in memory. In this manner the signal is averaged. There is also a recursive averaging mode which essentially works like an R/C circuit on the image, in which the time constant of image changes is effectively lengthened. All data acquisition is done in real time, which means acquiring a field of data takes 1/60 second.

In the normal mode of operation a 15 bit summation memory is cleared, then new data is accumulated for 256 fields after being shifted down 8

places. If a background subtraction is to be performed, the camera is shuttered, and 256 frames of data are subtracted from memory after being shifted down 8 places. The upper 8 bits of the resulting image are transferred to the second 8-bit image memory to provide a stable operator display. The three graphic memories are overlayed on the video in the output stage. One overlay contains all star, calibration and heading data. The other two overlays are each dedicated to a telescope and show that telescope's position and satellite choices.

At the ETS we have two telescopes, and the three video outputs are configured as an A system output, a B system output, and a supervisory output. All outputs have the same basic image, that of the current sky picture in a holding memory, and all have the common overlay of star, calibration and heading data. The A system has the A system overlay, the B system has the B system overlay and the supervisor has the overlays from both systems.

The graphics capabilities of the video processor include character generation in normal or reverse video, positioned anywhere on the 256x240 grid. Characters are a 5x7 matrix in a 7x9 box, with double high and double wide modes available. Lines can be drawn in normal or reverse video connecting any two points, and rectangles can be drawn by specifying two corners.

Data can be read from or written to image memories at a basic rate of 1.6 microseconds per pixel, although the computer cannot match this speed. The video processor can read out pixels in any direction, horizontally, vertically, or diagonally.

The processor also contains the ability to add or subtract image memories to form a display, and to run the video through a lookup table to generate arbitrary functional mapping. Since these features are not being used they will not be described further. Figure 8 is a block diagram of the video processor as it is used in the PANSKY system.

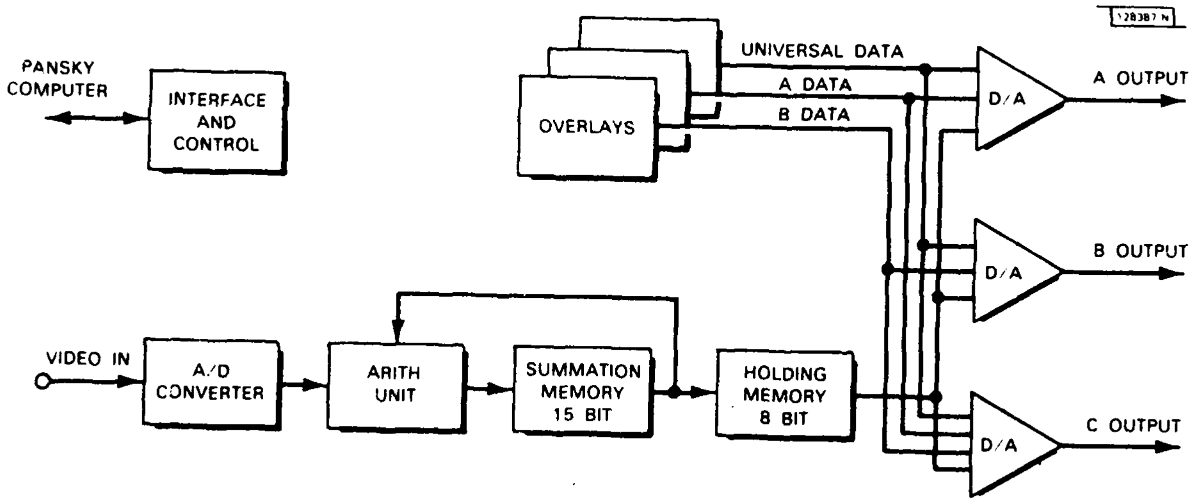

Fig. 8. PANSKY video processor.

PANSKY Computer

The PANSKY computer is based on the 8/16 bit MC6809 microprocessor and includes an AM9511 math processor. It is composed primarily of commercial Motorola Micromodule boards which use the EXORBUS interconnect. Several custom boards are used to provide unique capabilities. The main operator input is a 32 button panel with computer controlled backlighting. The PANSKY computer controls the entire PANSKY system, and also computes star positions, maintains system calibration, and interfaces with the central site computers.

The computer is programmed primarily in PASCAL, with a few assembly language subroutines and startup routines employed. When the project was started, an adequate compiler was not available, and the program was done in assembly. As better compilers became available and the program was refined, more and more was done in PASCAL. Even more could be done in PASCAL than is the case in the current implementation. All software development and system emulation was done on a Motorola Exorcisor development system, using an excellent compiler from Omegasoft.

This will be primarily a hardware description. The software description will be included in the system operation description in a following section. It is the PANSKY computer software which defines system function.

The computer system consists of 8 boards. They are MPU, PROM, RAM, CMOSRAM, PANSKY Support, Grinnel Interface, shared memory, and Quad ACIA. There is also in the ETS system an analog to digital converter board which performs a system function not related to PANSKY. The system is housed in a 14 slot chassis. A block diagram is given in Fig. 9.

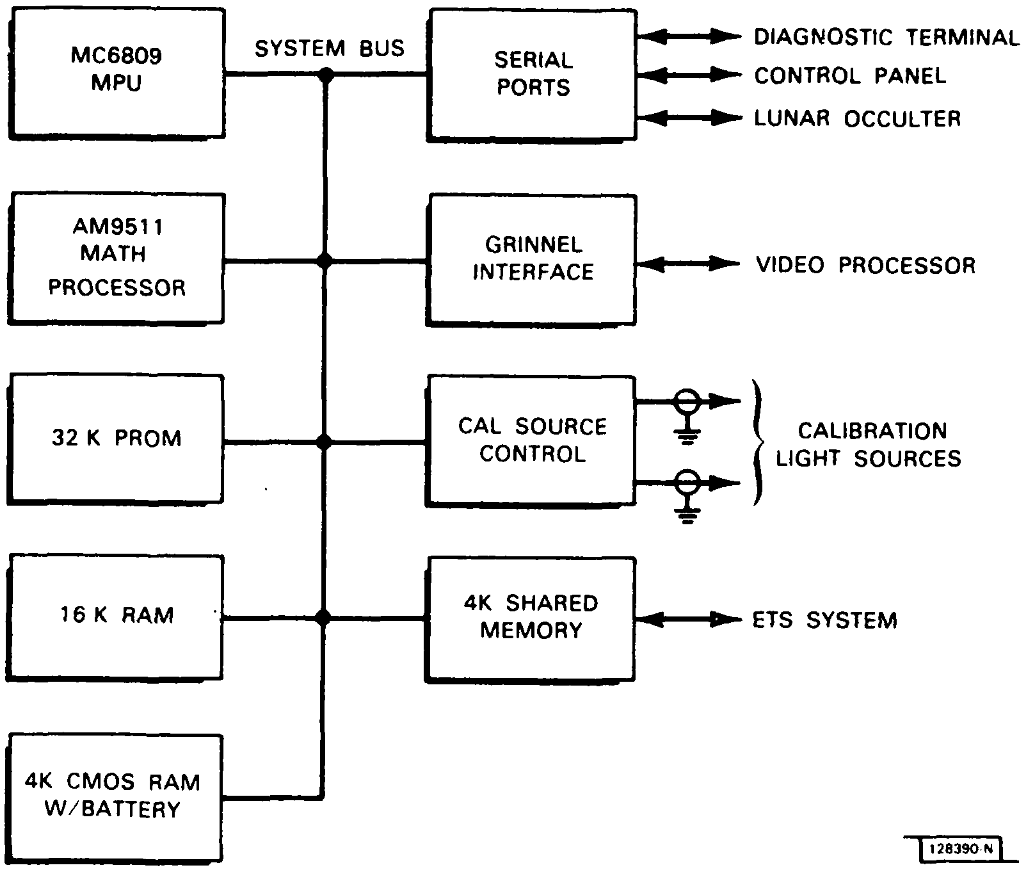

Fig. 9. PANSKY computer.

The MPU (microprocessing unit) board is a Motorola MM19 board which contains the MC6809 microprocessor operating at 1Mhz. It also contains a diagnostic serial port, 2K of RAM, and a PROM containing the interrupt vectors. The board also contains a PIA, timer, and more PROM sockets which are not used.

The PROM board is a Motorola MM04A board which will hold 32K bytes of 2716 type PROM. The current program and star catalog occupy 28K bytes of this board.

The RAM board is a Motorola MEX6816-22S which contains 16K bytes of static RAM, which is used for general variable storage.

The CMOS RAM contains a rechargeable battery which makes it non-volatile. The Motorola MM09 board contains 4K of static RAM which is used for system calibration parameters, and also general variable storage. The intent was to reduce the need to recalibrate during system development by preserving the calibration parameters from one night to the next. In practice the calibration procedure was made very simple, the system is seldom turned off, and parameters need adjusting anyway, so the non-volatile nature of this memory is not strictly required. A default set of calibration parameters is held in PROM to provide a starting point for recalibration.

The PANSKY Support Module contains two computer controlled constant current sources for the calibration light sources. It also contains the AM9511 math processor running at 2.5 Mhz. This processor is used for all floating point math calculations. An alternate runtime library for the PASCAL compiler is used to implement this feature without complicating the software. Since the compiler uses the same floating point format as the AM9511 this

change was easy to make. The AM9511 does not only the basic operations of add, subtract, multiply and divide, but also trigonometric and logarithmic functions and integer to floating point conversions.

The Grinnel Interface Module is the interface to the video processor and also to a time code reader for obtaining sidereal time. The module contains 2 parallel interface adaptors (PIA) with a total of four 8-bit programmable ports. Two ports are used together as a 16-bit channel for commands to the video processor. One port is used to read 8-bit data back from the video processor. The last port is used to read sidereal time from a time code reader. The reader is a standard IRIG-B reader which has been specially modified to multiplex the upper 16 bits of daily time in BCD into one 8-bit data port. The time resolution is therefore 10 seconds, which is sufficient for the PANSKY system. In the later evolutionary stages PANSKY was interfaced to the ETS console systems, and could obtain sidereal time from that source, making the time code reader unnecessary.

The Shared Memory Module is the interface to the ETS console systems, and through them to the main site computers. The memory system consists of a 3 port memory of 4K bytes size. The memory physically resides in the PANSKY system, with ports to the A and B console microcomputers. From the consoles PANSKY receives the current telescope positions. The consoles also support a data transer from the main site computers directly into the shared memory, which is used by PANSKY for obtaining satellite positions from the dynamic scheduler program. GMT and sidereal times are also available in the shared memory.

The Quad ACIA module is a Motorola MM07 card containing four serial interface ports. At present all ports are set for 9600 baud RS-232 communication, but only two are being used, one for the control panel and one for the lunar occulter.

Local Control Panel

The local control panel is a self contained unit which has 32 momentary push buttons with controlled backlighting. The panel contains a microprocessor based logic board which performs button debounce and encoding functions. One button is used for internal self test purposes. When a button is depressed, the button number is reported to the main PANSKY computer over an RS-232 serial link operating at 9600 band. The host computer decides whether to change the state of button backlighting or not. No action is taken when a button is released.

The control panel also has 16 peripheral driver circuits available on its rear panel. One of these drivers is used to control the camera shutter function. The driver appears to be just another button backlight to the host software.

A picture of the control room electronics, including the control panel, video processor, PANSKY computer, and camera remote control unit is given in Fig. 10.

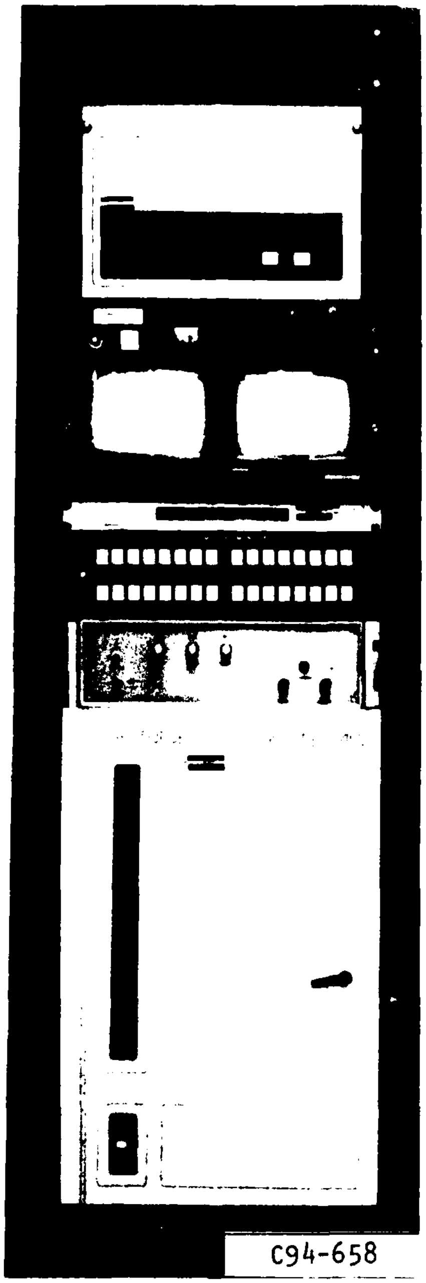

Fig. 10. PANSKY electronics rack in control room.

VI. SYSTEM SOFTWARE

The sky monitor software is organized into several successive levels, as shown in Fig. 11. On power up a monitor type program is entered, which has commands for debugging purposes and can also enter the main program. The main program enables interrupts, and all subsequent program execution is in response to interrupts from the control panel. Certain control panel initiated programs (the main operating modes) can themselves be interrupted by the control panel.

The monitor program initializes the system, initializes the diagnostic terminal interface, and then checks the DTR (Data Terminal Ready) line to see if a terminal is attached. If no terminal is attached, then the main program is run. If there is a terminal, then a command entry level is entered. Functions available at this point are basic memory examination and change, memory listing, and system reinitialization, as well as the main program, a diagnostic routine for the video processor, a standalone test of star catalog and position calculation routine, and a routine for setting the positions of the landmark LED's for the calibration system.

When the main program is entered, either from the monitor command level or automatically if no diagnostic terminal is present, the interrupt from the control panel is enabled and a waiting loop is entered. All system action is now in response to control panel button pushes. The monitor can be reentered by the ABORT button on the computer chassis, and the whole system reset by the RESET button.

Most button run routines are of finite length, which do such things as modify calibration parameters, run diagnostics, or adjust the lunar occulter.

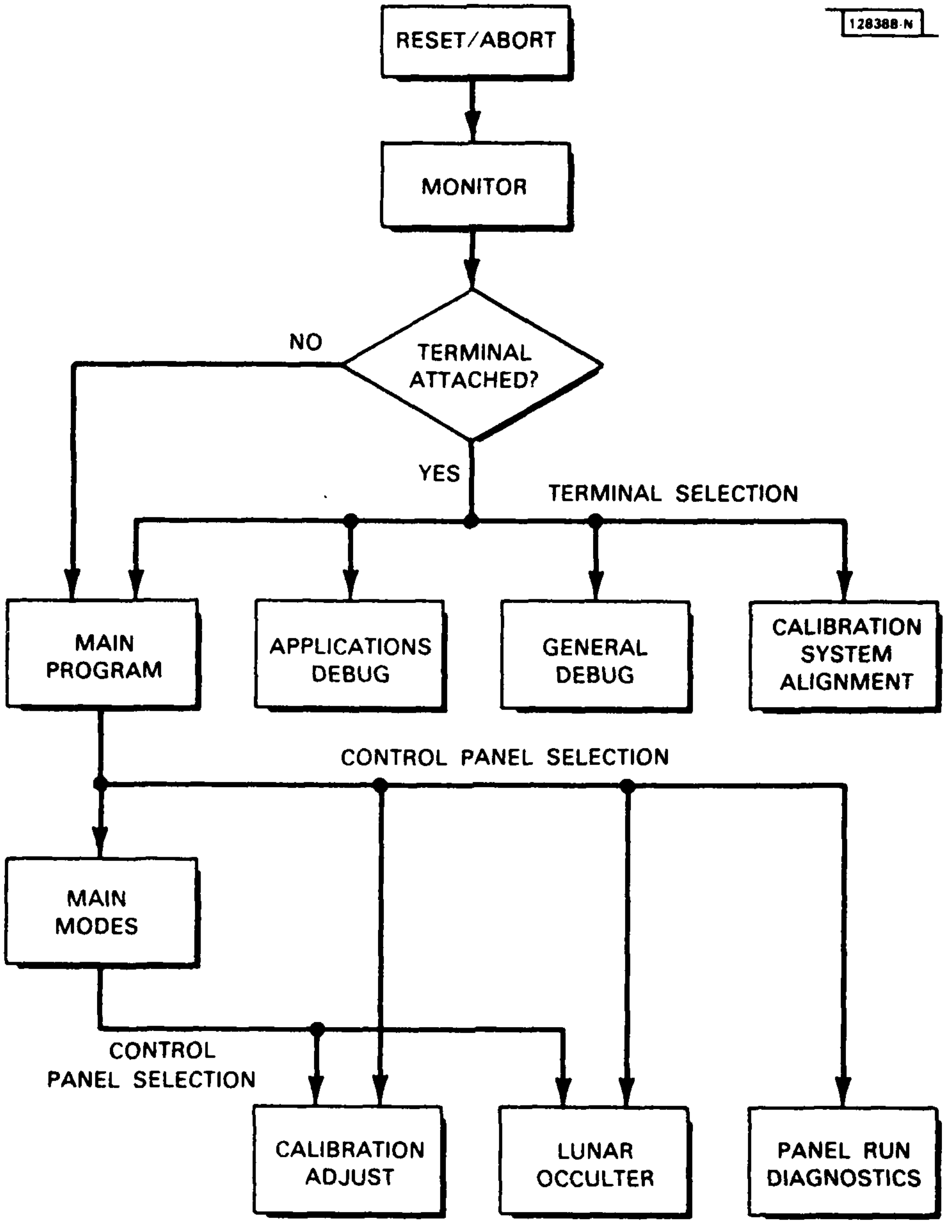

Fig. 11. PANSKY software organization.

The major operating modes are entered via the control panel, and do not terminate, but continue to run until system ABORT, RESET, or power down. Button routines which affect calibration parameters can be run while the system is in an operational mode, but button routines which use the video processor for its graphics capability will interfere with the operational programs.

Three main areas of software operation during the operational modes are video processor control, operations involving the metric calibration of the system, including star position prediction, and operations involving signal measurement, including the photometric calibration and extinction calibrations. The video processor sequencing has been covered in the system overview section, and the other two areas will now be described. The action of each of the control panel buttons will also be explained in Appendix C.

Calibration and Coordinate Conversion

It is necessary to convert from star coordinate and telescope and satellite positions to positions on the television image. The television image is a 256x240 array of pixel values produced by the video processor.

All object positions are first converted to azimuth and elevation forms. Stars are converted from right ascension and declination to this form by the equations:

$$HA = RA\text{-}TIME$$

$$EL = SIN^{-1}(SIN(DEC)*SIN(LAT)+COS(HA)*COS(DEC)*COS(LAT))$$

$$R1 = COS(HA)*COS(DEC)*SIN(LAT)-SIN(DEC)*COS(LAT)$$

$$R2 = -SIN(HA)*COS(DEC)$$

$$AZ = TAN^{-1}(R2/(-R1))$$

where RA = right ascension of star

TIME = sidereal time

HA = hour angle

LAT = latitude of sensor

EL = elevation

AZ = azimuth

Calibration System Operation

Since the conversion is time dependent, it must be repeated continually, and this is the heaviest computational load on the PANSKY computer. Calibration light source positions are held as azimuth and elevation, and telescope positions may be handled as right ascension, declination or az, el.

The conversion from az, el to screen position involves several parameters, most of which are actively maintained at their correct values by the calibration system. The lens is assumed to be axially symmetric, and the elevation angle is first changed to radial distance on the camera faceplate. The function involved is characteristic of a true fisheye lens design and is:

$$RLENS(\theta) = A*\cos^{-1}\theta \qquad (1)$$

where RLENS = radial distance in focal plane

A = scaling factor

θ = elevation angle (0=horizon)

The screen positions are then given by

$$X = XFAC*RFAC*RLENS(\theta)*\sin(AZ-\phi_0)+X_0 \qquad (2)$$

$$Y = RFAC*RLENS(\theta)*\cos(AZ-\phi_0)+Y_0 \qquad (3)$$

where A in equation 1 has been absorbed in a more encompassing radial scale factor RFAC. The factor XFAC is an x-axis only scaling factor used to compensate for the rectangular nature of the camera beam scanning pattern. The X_0 and Y_0 are the screen coordinates of the zenith point in the video processor coordinate system. Since the video processor is a 256x240 system with the origin in the lower right corner, X_0, Y_0 is approximately 128,120. The angle ϕ_0 is a correction for misalignment of the camera with true north. XFAC, RFAC, X_0, Y_0 and ϕ_0 are all maintained by the calibration system.

The calibration system operates by knowing the actual and measured positions of the four calibration light sources. The light source positions are themselves calibrated by reference to the stars, but the system cannot be routinely calibrated by stars because the whole point of the system is to look for stars which may not be visible due to clouds.

The camera image is searched at the predicted light source position (which is dependent on the current calibration parameters) for the image of the source, and the X and Y errors are measured. All parameters are then adjusted a fixed amount in the direction required to bring the predicted and actual positions closer. The equations used are:

$$X_{corr} = \sum_{i=1}^{4} \Delta X_i \qquad Y_{corr} = \sum_{i=1}^{4} \Delta Y_i$$

$$RFAC_{corr} = \sum_{i=1}^{4} \Delta X_i * X_i + \Delta Y_i * Y_i$$

$$XFAC_{corr} = \sum_{i=1}^{4} \Delta X_i * X_i$$

$$\phi_{corr} = \sum_{i=1}^{4} \Delta X_i * Y_i$$

where ΔX_i and ΔY_i are the measured errors at the landmark positions, in the range -3 to +3. X_i and Y_i are vector components to the landmark positions from the position X_0, Y_0.

The amount of correction in each case corresponds to a change in predicted position of about one half pixel at the edge of the field of view. For instance, if X_{corr} greater than 0, then 0.5 pixel is added to X_0, and if less than 0, 0.5 pixel is subtracted from X_0. Predicted positions constantly dither about the true position, but the accuracy is sufficient for the purpose and the system is stable.

The primary display associated with the metric calibration system is four small boxes drawn around the calculated positions of the calibration light sources, or landmarks. If the landmarks appear in the center of these boxes, then the system is calibrated. The size of the box indicates the pull in range of the automatic system. If all four landmarks are within their respective boxes, then the automatic system should be able to refine and maintain the calibration.

If the landmarks are outside their boxes, then the system must be manually adjusted. Control panel buttons are provided in pairs for adjusting X_0,Y_0, RFAC,XFAC, and ϕ_0 with one button of the pair increasing the parameter and the other decreasing it. A button activated routine will redraw the landmark position boxes at the location corresponding to the adjusted parameters. This procedure is usually required at the beginning of a night's operation, before the main operating mode is engaged.

Another button routine will draw a box around all calculated star positions. This provides a test of the star position calculation (and sidereal time reading), as well as a method of aligning the calibration system. In addition to the panel controls for the calibration parameters, another set of buttons control the magnitude limit for the stars deployed, allowing the number of stars to be controlled.

Calibration System Alignment

The calibration system alignment consists of determing the azimuth and elevation of the calibration light sources, which are then used as working standards for all other positions. The sources are calibrated using stars as the fundamental position reference. This procedure can only be run from the monitor command level of the software, so a diagnostic terminal is required to be attached to the system. The control panel is active when in the monitor command entry level, and the first step in aligning the system is to use the calibration adjust buttons along with the star position display routine button to adjust the calibration parameters until the predicted star positions match the real positions.

The routine 'CAL' is then entered from the monitor. The terminal will then prompt for input. Each calibration source is selected in turn and its box position adjusted until the source image falls in the center of the box by using keys on the terminal to incrementally adjust the azimuth and elevation coordinates. The refined coordinates are listed on the terminal and entered in non-volatile memory. Under some circumstances the non-volatile memory is initialized from the program PROM, so the correct coordinates should at sometime be put into PROM.

Signal Measurement

A common task for both calibration and star extinction determination is the measurement of the position and intensity of a point source image. While the image as projected on the camera faceplate is smaller than a pixel, when the signal is digitized the energy may be spread over more than one adjacent pixel.

The signal measurement process starts with a predicted object position on the picture. A 7 by 7 pixel array is read back from the video processor as 15 bit values, centered on the predicted object position. The brightest pixel is found, and its position used as the position of the object. A 3 by 3 array of pixels at this location is considered to contain all the point source energy, so all the pixels of the 7 by 7 array which are not in the 3 by 3 are added together to form a background value. The brightest pixel and the next brightest adjacent to it are summed, and the normalized background is subtracted to form the signal magnitude. In the worst case of energy evenly split between four pixels, 50% of the signal will still be recovered. This will still give system accuracy sufficient for scheduling purposes. A correction for camera tube shading (decreased sensitivity at the edge of the field of view) has not been found to be necessary.

The signal magnitude is calibrated by using one of the calibration light sources as a photometric standard. The light source is a current controlled LED, and it should be fairly stable. On a clear night its intensity is adjusted to correspond to a 1st magnitude star by direct comparison. Calibration with an artificial star corrects for any lens and se[illegible] chain drifts, since the calibration source and the stars are affected equally.

A magnitude limit is set based on the size of the calibration signal and an estimate of system noise which limits which stars can be used. The limit is set such that all stars above the limit can still be detected when they have 2 magnitudes of extinction. This prevents display clutter by stars which cannot be measured accurately enough to determine extinction. The number of stars used varies with system conditions. If the lens is stopped down, for instance, the calibration signal will decrease, and fewer stars will be used. The measured magnitudes of the stars will still be accurate.

This feature, along with the variety of stellar magnitudes, allows for graceful system degradation. If the system is not working well, fewer stars are used. This decreases the system spatial resolution, but the system continues to work.

The measured star magnitude is compared to the catalog value to determine the extinction. If the extinction is greater than or equal to 2 magnitudes, a cloud is considered to be occluding the star. Extinctions less than 2 magnitudes are displayed by a number 0-3 representing the half magnitudes of extinction. This allows the operator to assess system performance. This scheme was devised for the development phase of the sky monitor. The best display for the operator would be a straight clear/cloudy indication. An example of the display is given in Fig. 12.

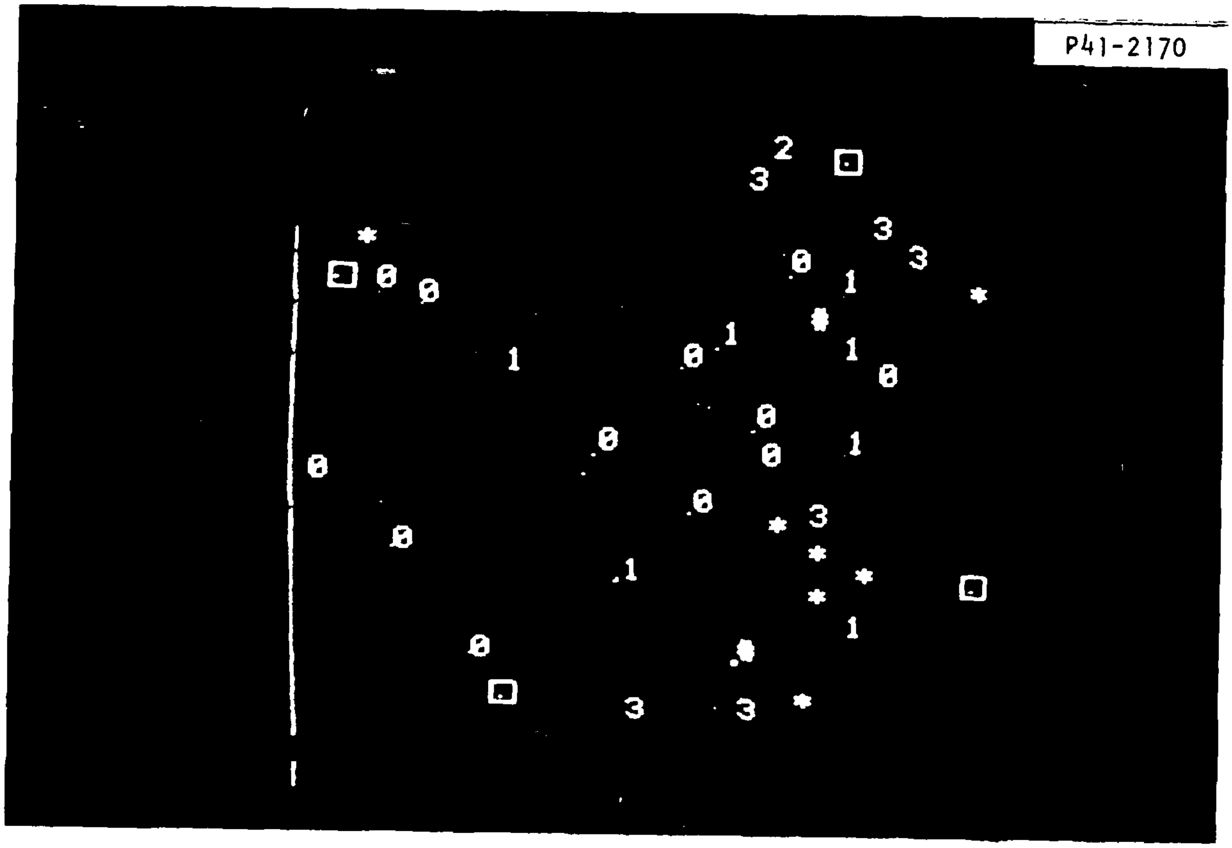

Fig. 12. Dark sky mode display. Numbers represent half magnitudes of extinction at the position of the lower left corner of the numeral. The area marked by '*' at the lower right denotes an occluded area caused by an artificial blockage.

V. RESULTS AND CONCLUSIONS

The system described was initially installed at the ETS in New Mexico in March of 1980. The calibration system was installed in October of 1980, and cloud detection by occultation of starlight demonstrated in March of 1981.

At this point we had a significant degradation of the ebsicon. Picture lag became large, the dynamic range of the tube decreased, and the signal became much smaller. Of all the effects, the decreased dynamic range was the most serious, for the dark sky mode of operation depends on being able to measure stars of widely varying magnitudes.

The tube degraded all summer, and by the time the system was integrated with the dynamic scheduler in the fall of 1981, the camera was so bad that the camera head was removed. A new tube was obtained and the camera head reinstalled in February of 1982. When the camera was reinstalled, the weather was clear and a test of the dark sky mode was not possible.

From the end of February to the middle of July the system was operated on a nightly basis by Air Force personnel during routine operations of the ETS. The system was used in the semiautomatic, bright sky mode. Attempts to collect usage statistics automatically were only partially successful. It is known that the scheduler interface worked well, and operators were making satellite selections based on the Panoramic Sky Monitor display. Verbal comments of the operators indicated that they liked the system very much, as it saved them numerous trips outside during unsettled weather. The only significant complaint was the increased time used by the scheduler program, but this is a function of the scheduler implementation in the central site computer.

On several occasions the clouds were low and moving rapidly, and with the slow telescope mounts of the ETS, holes could not be exploited. In such situations the PANSKY display keeps the operator well informed of the cloud status, even if no work is possible at a given moment. When the sky clears, even momentarily, work can be immediately resumed.

At the end of the test period the lunar occulter was installed, and it was noticed that the replacement ebsicon was failing in the same manner as the original. The camera was again returned to Lexington, and the problem discovered to be a contamination of the electron gun cathode. Baking the tube cured the problem, and running the tube heater a little warmer is expected to keep it from recurring.

The ETS system could be reproduced using commercially available computers, video processors, and ebsicon cameras. Some features desirable in a new system would be a 512 by 480 resolution video processor, remote control of the lens aperture (even automatic control), and remote control of the rooftop enclosure cover. The dark sky mode would most likely work, but not with the full range of stars, and therefore spatial resolution, deemed desirable. The calibration system worked quite well for taming the metric problems of the television camera.

While an ebsicon television based system would be very useful, a system based on a CCD camera would be better due to the increased dynamic range and metric and photometric stability of the solid state sensor. The increased dynamic range would allow the dark sky mode to function more completely, and would allow the system to operate in twilight conditions. The sensor would be less susceptible to damage from high light levels, but still could not stand

the direct image of the sun during the day. Figure 13 is a graph comparing the existing television system with external integration, a slow scan television system, and a CCD system for dynamic range. With an integration time of 5 seconds or more, even a fairly noisy device such as the RCA 512x320 CCD is more sensitive than an ebsicon, and is superior in saturation characteristics. However, no commercial CCD cameras are adequate for the job because the device must be cooled, and CCDs large enough to work with known lens designs are not yet available. The GEODSS program is expected to produce a suitable device within the next year.

A possible strategy would be to procure an ebsicon based system, and upgrade later to a CCD. Almost all components of the ebsicon system would be retained, with a CCD sensor head and CCD video processor required for the upgrade. The existing video processor could still be used for display formation.

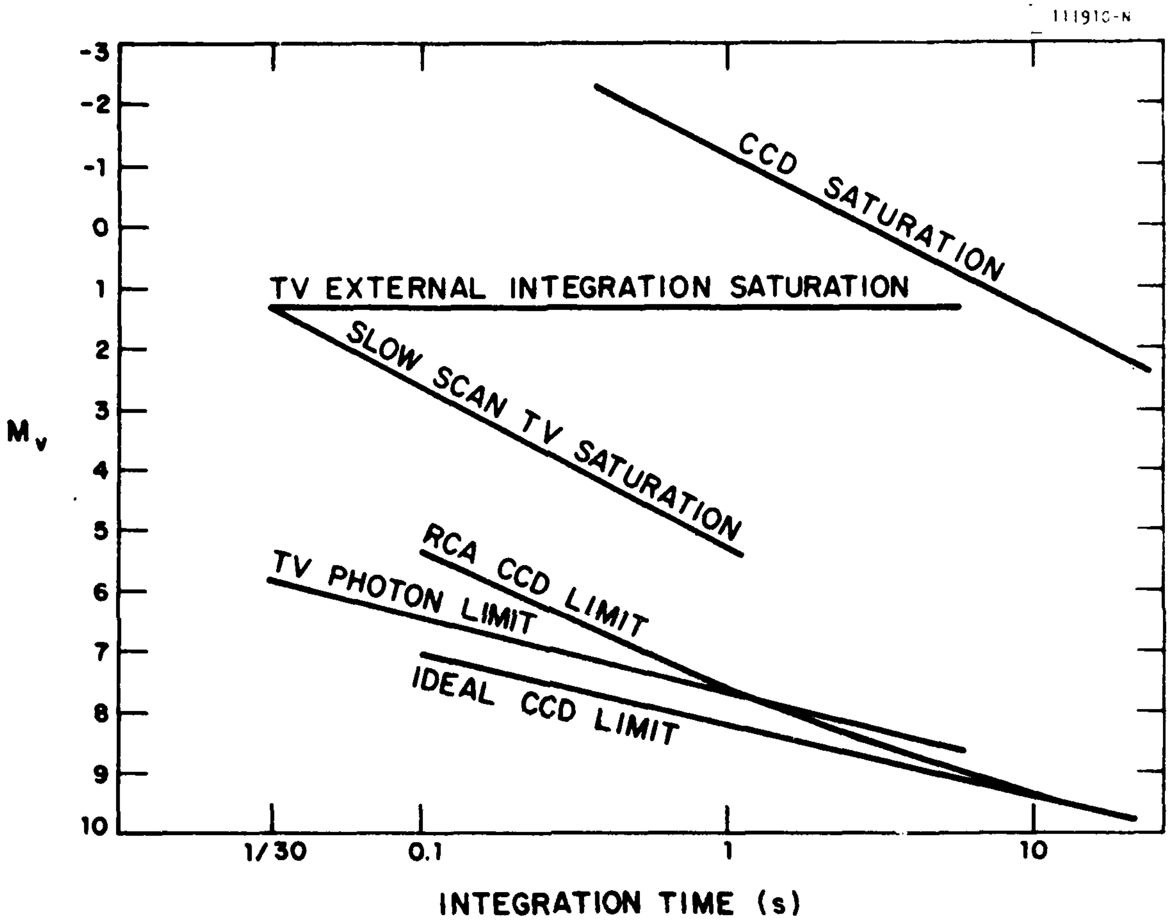

Fig. 13. Sensor dynamic range as a function of integration time for different sensor types.

APPENDIX A

SENSOR THEORY

The sensor signal to noise ratio can be calculated based on the parameters of the sensor system. The signal due to a star is given by

$$S(M) = \Phi_{S-20}\ Aqt\ 10^{-0.4Mv}\ \text{photoelectrons}$$

where Φ_{S-20} = 5×10^6 photons/cm^{2}sec, the flux for a 0 magnitude star for the S-20 spectral response

A = optical collection area

q = detector quantum efficiency

t = total integration time

M_v = visual magnitude (S-20) of the star.

For the current system:

$$A = \frac{\Pi}{4}\left(\frac{F}{f}\right)^2 = \frac{\Pi}{4}\left(\frac{16mm}{2.8}\right)^2 = 25.65mm^2 = .26\ cm^2$$

q = 0.07 for the SIT

t = 256/60 seconds = 4.27 seconds

therefore

$$S(0) = 3.89 \times 10^5\ \text{electrons}$$

The sky background level is given by

$$B(NSB) = \Phi A\ \alpha^2 qt\ 10^{-0.4NSB}$$

where α = pixel angular size in $\widehat{sec}^{\,2}$

NSB = night sky background in Mv/$\widehat{sec}^{\,2}$

For the current system

$\alpha \approx 0.5$ deg = 1800 sec

The system noise level is then

$$N = \sqrt{B + N_I^2}$$

where N_I is the instrument noise. In the case of the SIT the instrument noise is very low, so the sky background noise can be considered to dominate. The signal to noise ratio (SNR) for a 5th magnitude star under a 19 mag/sec ^{2} sky is then:

$$SNR = \frac{S(5)}{\sqrt{B(19)}} = \frac{3.89x10^3}{\sqrt{3.16x10^4}} = 21.9$$

When the star is dimmed by 2 magnitudes, the SNR is then 3.5, so our theoretical sensitivity is marginal for working with 5th magnitude stars.

APPENDIX B

STAR SELECTION

The number of stars required to form a grid is dependent on the resolution required. The system sensitivity needed to see the stars of the grid depends on the distribution of star magnitudes. To use a finer grid means using more stars, therefore dimmer stars, and requires a greater system sensitivity.

A 10° grid is one star for every 100 square degrees. From Fig. B-1, the limiting magnitude required to average one star per 100 deg^2 is about 3.8. However, there are certain holes in the grid which require the use of dimmer stars, and in fact 5th magnitude stars must be used.

Star selection started with the FK4 catalog stars, whose positions have been accurately measured. The stellar magnitudes were converted to S-20 response. A critical spacing was defined, which in this case was about 7 degrees, and a sensitivity limit established, which was 5th magnitude. The selection procedure then consisted of two passes through the catalog. All stars below the sensitivity limit were ignored. On the first pass, all stars which had a brighter star within the critical distance were deleted from the catalog. On the second pass, stars which had been deleted, but which had no brighter star remaining in the catalog closer than the critical distance, were restored to the catalog. This was to avoid the situation where star A is deleted because it is close to star B, but star B is deleted because it is close to star C, and star A is far from star C. In the second pass star A is restored to the catalog, but star B remains deleted.

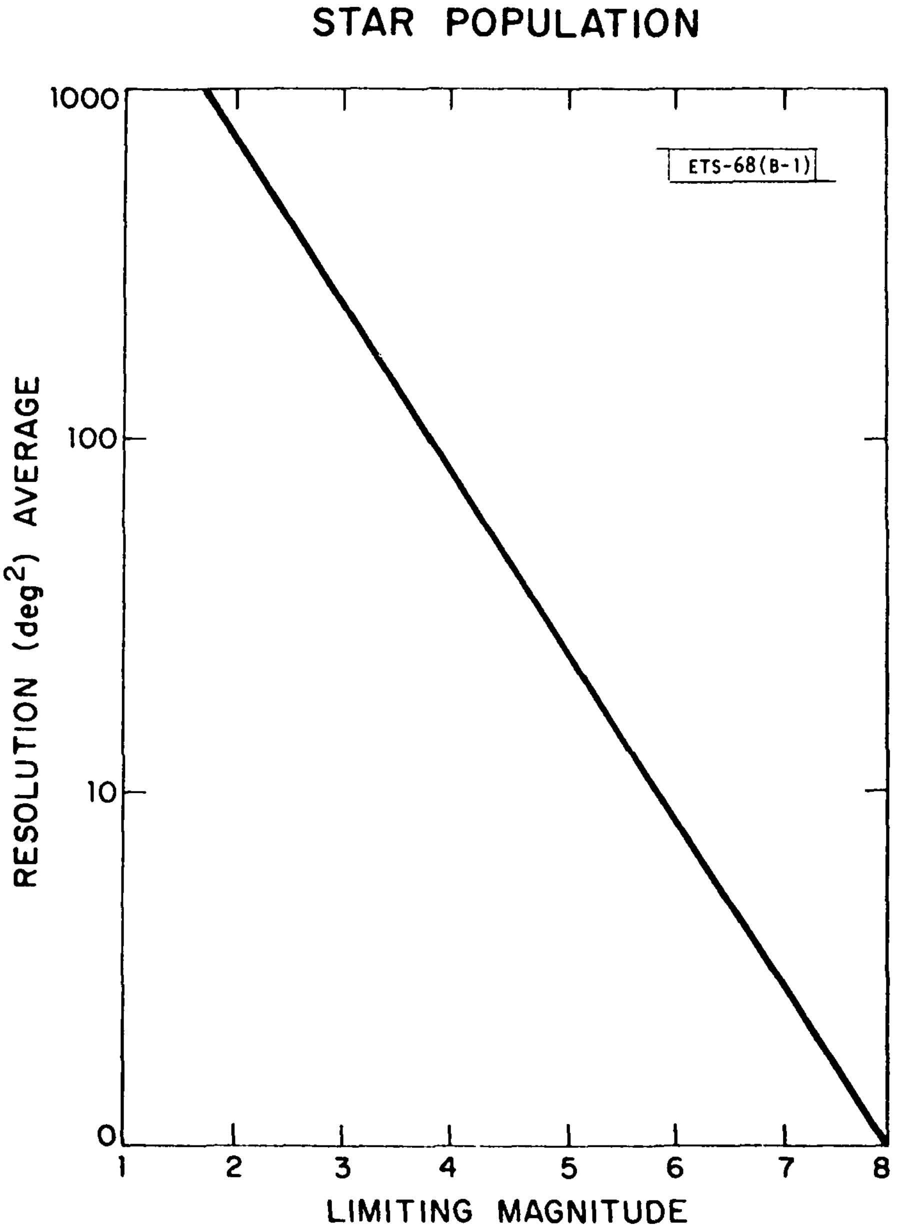

Fig. B-1. Star population density. From Allen, "Astrophysical Quantities".

APPENDIX C

CONTROL PANEL FUNCTIONS

The control panel consists of 32 buttons. When a button is pushed, the button number is reported to the PANSKY computer, which decides what action to take. It is the PANSKY computer software which defines the function of each button, and controls the backlighting of each button. Figure C1 shows the button arrangement and number assignments, and the button functions are given below.

0. SELF TEST - Activates control panel self test functions. When held, hitting any other button will cause the state of backlighting of that button to toggle.
1. GMR TEST - Reinitializes the video processor and its interface and runs the video processor internal test #0.
2. LUN OCC ON - Toggles the backlight. When the backlight comes on, the lunar occulter is enabled and moves to the center position. When the light is turned off, the occulter is disabled and moves to a stowed position.
3. LUN OCC EAST - Toggles the light. When the light is on, the lunar occulter moves east. Used for manually positioning the occulter.
4. LUN OCC WEST - Same as 3 but moves the occulter west.
5. CALINI - Copies the calibration parameters from PROM into RAM, restoring an old, known set. This can also happen automatically, in which case the light is lit to indicate it has happened.

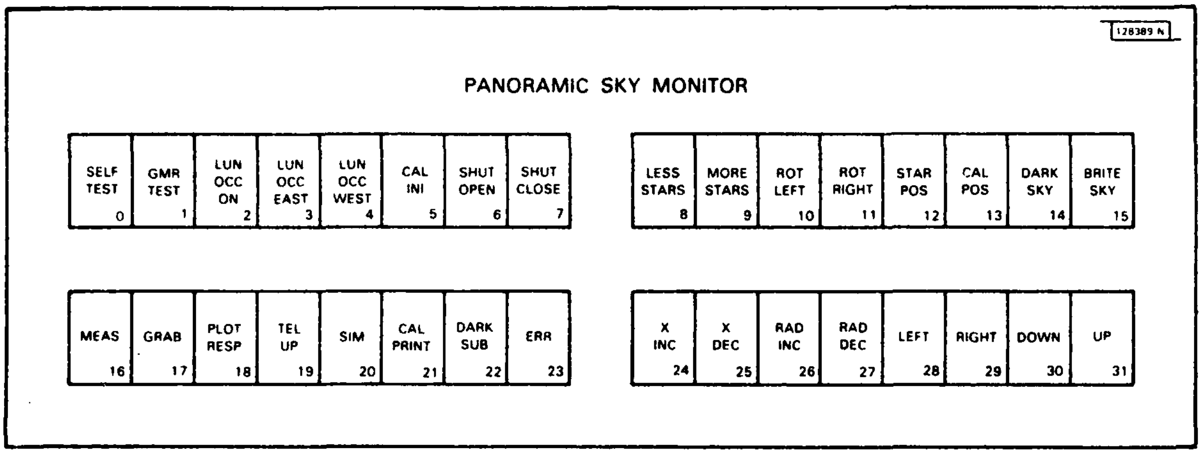

Fig. C-1. PANSKY control panel.

6. SHUT OPEN } - Opens and closes the camera electronic shutter
7. SHUT CLOSE } when operated manually, also indicates the current shutter position.
8. LESS STARS } - Controls the magnitude limit for star display
9. MORE STARS } in 1/8 magnitude increments. The value set will be overridden by an automatic system in normal operation.
10. ROT LEFT } - Adjust the rotation parameter ϕ_0 for calibration
11. ROT RIGHT } manual adjustment.
12. STAR POS - Displays a box around calculated positions of all stars brighter than the current magnitude limit. Used for calibration system alignment.
13. CALPOS - Displays a box around the calculated calibration light source positions. Used for calibration manual adjustment.
14. DARK SKY - Runs dark sky operational mode without background subtraction.
15. BRITE SKY - Runs bright sky operational mode without background subtraction.
16. MEAS - Measures the signal strength at the zenith position. Only used for advanced diagnostics.
17. GRAB - Fills video processor memory with current picture for MEAS routine. Only used for advanced diagnostics.
18. PLOT RESP - Plots camera intensity-signal strength curve by ramping light source. Only used for advanced diagnostics.

19. TELUPDATE - Plots current telescope and satellite locations on display. Normally done automatically.

20. SIM - Controls simulated mode. When in simulated mode (button lit), the signal measurement routine always returns a perfectly centered star, allowing the system to be run without the sensor turned on. This prevents the automatic calibration system from modifying the stored constants.

21. CAL PRINT - Prints the current calibration parameters on the diagnostic terminal. Only used for debug and alignment purposes.

22. DARK SUB - Runs dark sky operational mode with background subtraction.

23. ERROR - Button turns off error light, which may be lit by program.

24. X INC } - Controls parameter XFAC for manual
25. X DEC } calibration.

26. RAD INC } - Controls parameter RFAC, the radial size,
27. RAD DEC } for manual calibration.

28. LEFT } -Control X_0, translation, for manual
29. RIGHT } calibration.

30. DOWN } - Controls Y_0, translation, for manual
31. UP } calibration.

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A system has been designed and built for optically detecting clouds at night. Based on a low light level television camera with a fisheye lens, the system can detect clouds either by moonlight or by stellar occultation. The system is integrated with a scheduling program for the Experimental Test System (ETS) of the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) system to allow operations on partly cloudy nights.

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